Is the dark matter particle its own anti-particle?

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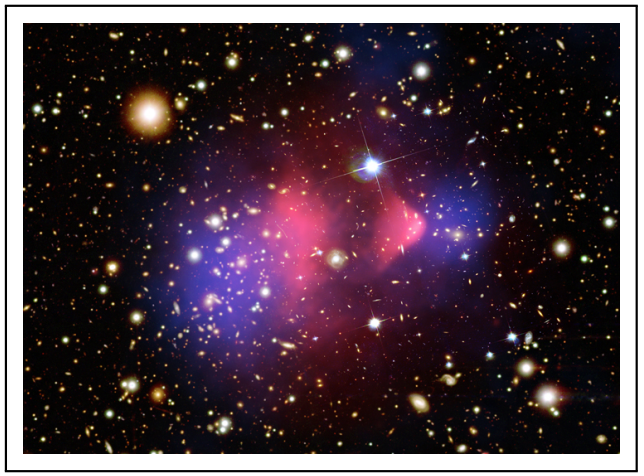
Experimental evidence for dark matter

The astrophysical evidence for dark matter is very strong.

- Galactic rotation curves
- Cosmic Microwave Background
- Big Bang Nucleosynthesis
- Gravitational lensing observations



The WIMP miracle

A Weakly Interacting Massive Particle is a theoretically well-motivated dark matter candidate.

- The relic abundance of a particle of a weak-scale mass interacting with weak-scale interactions is consistent with observations.

$$\langle \sigma_A v \rangle \sim \frac{g^4}{4\pi (1\ \mathrm{TeV})^2} \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

- It is an attractive proposition that with the already observed scales in the universe, we can explain dark matter.

Two recipes for dark matter models

Add Salt to taste

Use models of new physics at the weak scale which are motivated by some problem in the Standard Model.

- Supersymmetry solves the Planck-weak hierarchy problem.
- A simple discrete symmetry makes the lightest particle in this extension stable.
- The WIMP miracle ensures that it naturally yields present day relic abundance.

We get a dark matter particle "for free".

Two recipes for dark matter models

Microwave-ready dark matter

Minimally extend the Standard Model, introducing fewest additional degrees of freedom.

- As before, a symmetry ensures the stability of the dark matter particle.
- An extension as simple as a singlet scalar particle works.

Two recipes for dark matter models

Microwave-ready dark matter

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Most of the machinery in the first case is incidental from the dark matter physics perspective.

Model-independent analysis

What are the basic questions in dark matter physics?

- What is the mass of the dark matter particle?
- What is the spin of the dark matter particle?
- Is the dark matter particle its own antiparticle?
- What are the interactions of dark matter with the Standard Model?

  ⋮

Which of these questions can we answer using available (and future) experimental data, without restricting to a specific model?

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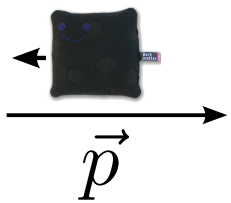
The CPT Theorem

For every particle there is an anti-particle with the same mass and spin but with an opposite charge(s).



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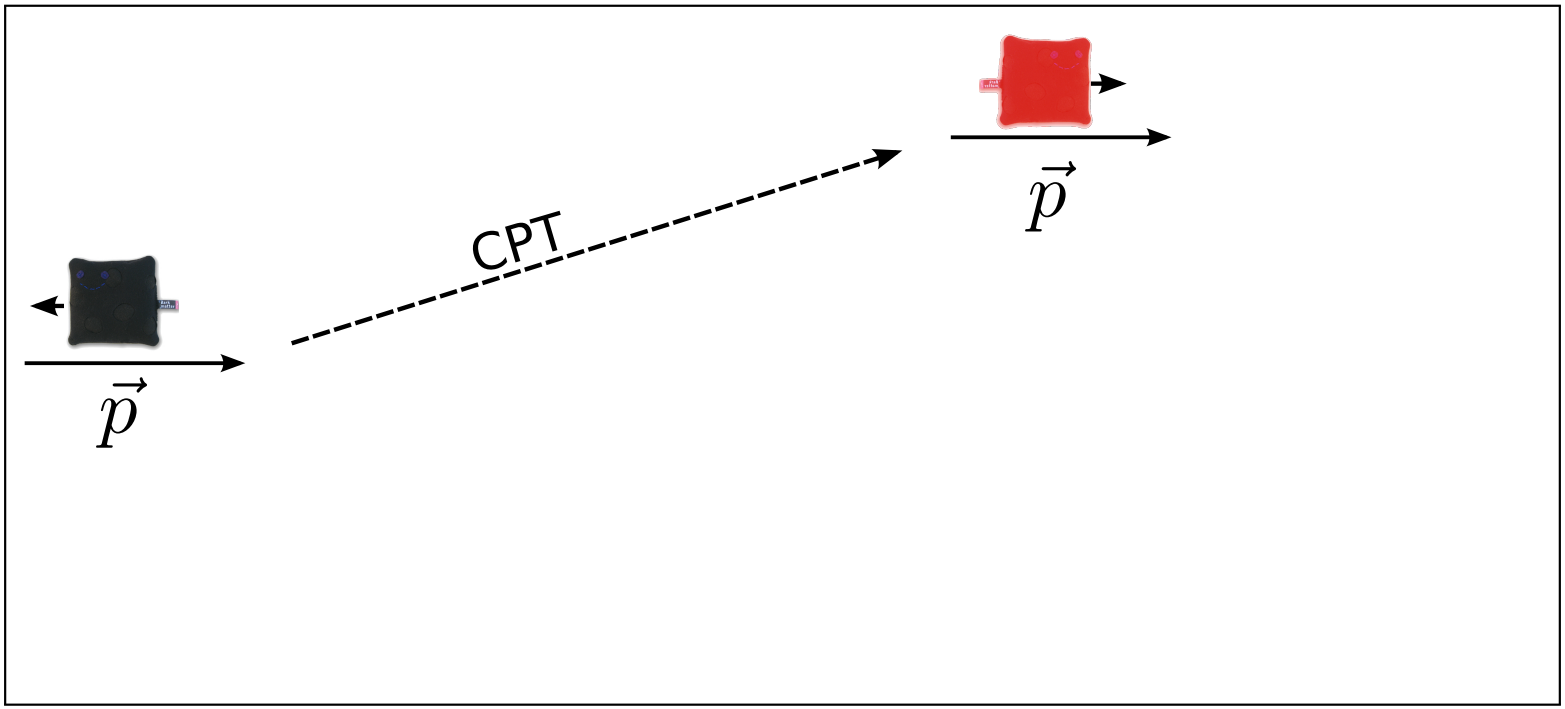

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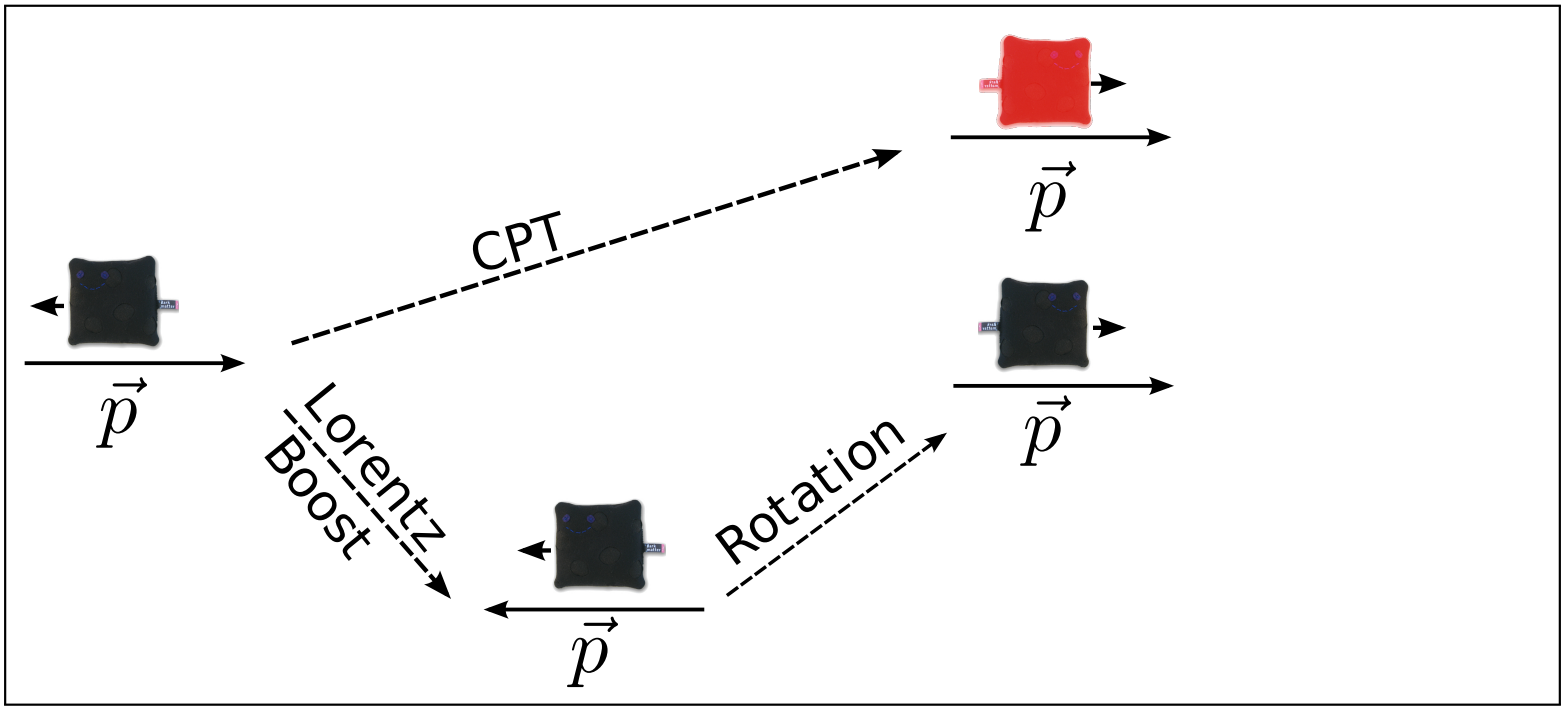

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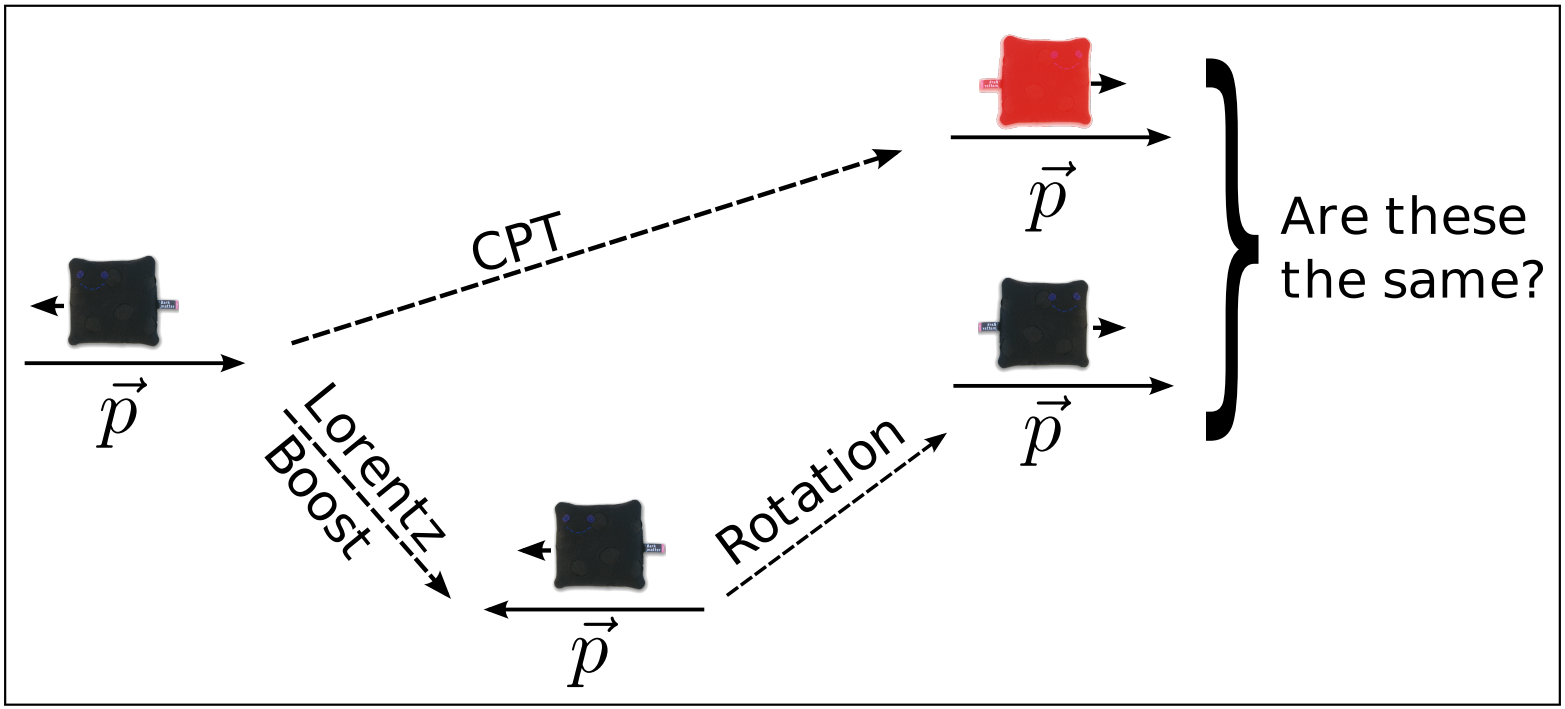

The answer

Non-relativistic WIMP interactions with protons (or neutrons)

- Spin-independent (SI)
- Spin-dependent (SD)

Theories where the WIMP-nucleon cross-section is **dominated by SD interactions** naturally arise from theories where the dark matter particle is **its own anti-particle**.

$$\sigma_{SD} \gg \sigma_{SI} \Rightarrow \chi = \chi^c \quad (\text{but} \quad \chi = \chi^c \not\Rightarrow \sigma_{SD} \gg \sigma_{SI})$$

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Which dark matter models give rise to a dominantly spin-dependent WIMP-nucleon cross-section?

Setup

- Cosmological limits constrain WIMP dark matter to be neutral under color and electromagnetism.
- Limit to theories where WIMP-nucleon scattering is elastic and arises at tree-level.
  - Only WIMP-quark coupling contributes to the WIMP-nucleon scattering.

$$\mathcal{O}_{\chi\chi qq} \sim \text{[DM bilinear] [quark bilinear]}$$

- Cross-section depends on the matrix element of quark bilinears between nuclear states.

Symmetry - Quark bilinears

Parity allows us to distinguish between SI and SD terms.
WIMP-nucleon scattering is non-relativistic.

The quark bilinears
depend on:

- Relative velocity $\vec{v}$
- Nuclear spin $\vec{s}$
- Charge(s) Q
- QCD scale $\sim m_p$
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Operator			NR limit
Scalar	$\bar{q}q$		$\frac{m_p}{m_\chi}$
Pseudo-scalar	$\bar{q}\gamma^5 q$		$\vec{s}\cdot\vec{v}\,\frac{m_p}{m_\chi}$
Vector	$\bar{q}\gamma^\mu q$	$\bar{q}\gamma^0 q$ $\bar{q}\gamma^i q$	Q Qv^i
Pseudo-vector	$\bar{q}\gamma^\mu\gamma^5 q$	$\bar{q}\gamma^0\gamma^5 q$ $\bar{q}\gamma^i\gamma^5 q$	$\vec{s}\cdot\vec{v}$ s^i
Tensor	$\bar{q}\sigma^{\mu\nu} q$	$\bar{q}\sigma^{0i} q$ $\bar{q}\sigma^{ij} q$	$v^i\,\frac{m_p}{m_\chi}$ $\epsilon^{ijk}s^k\,\frac{m_p}{m_\chi}$

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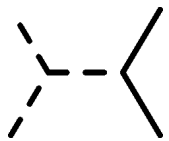
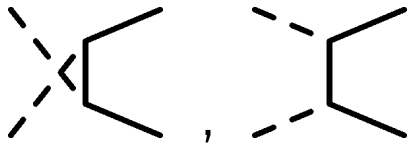
Scalar Dark Matter

Mediator	Process	Scattering
Z, Z'		SI
h		SI
Q		SI

Fermionic Dark Matter

The effective 4-fermion operators for the scattering process:

$$\bar{\chi}\gamma^{\mu}\chi\,\bar{q}\gamma_{\mu}q \qquad \bar{\chi}\gamma^{\mu}\gamma^{5}\chi\,\bar{q}\gamma_{\mu}q$$
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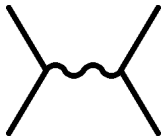
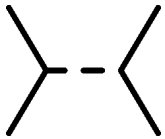
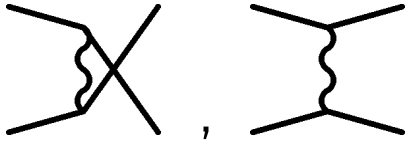
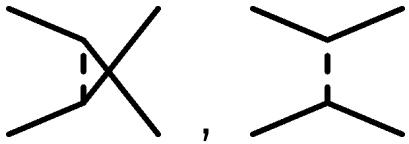
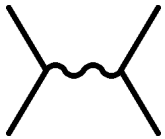
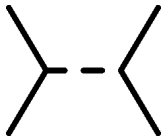
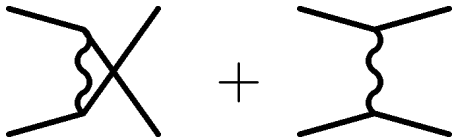
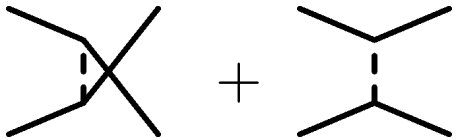
A consequence of the self-conjugacy of the Majorana field!

Dirac Fermion

Mediator	Process	Scattering
Z,Z'		SI, SD[†]
h		SI
X		SI, SD
Φ		SI, SD

[†] Can be primarily SD for specific choices of Z' charges

Majorana Fermion

Mediator	Process	Scattering
Z, Z'		SD
h		SI
X		SD (in chiral limit)
Φ		SD (in chiral limit)

Vector Boson

We can repeat the above operator analysis for vector boson dark matter.

$$\epsilon_{\mu\nu\lambda\sigma} B^\nu \partial^\lambda B^\sigma \; \bar{q}\gamma^\mu\gamma^5 q$$

$$B^\nu \partial_\mu B_\nu \; \bar{q}\gamma^\mu\gamma^5 q \qquad B^\nu \partial_\mu B_\nu \; \bar{q}\gamma^\mu q$$

$$B^\nu \partial_\nu B_\mu \; \bar{q}\gamma^\mu\gamma^5 q \qquad B^\nu \partial_\nu B_\mu \; \bar{q}\gamma^\mu q$$

$$\epsilon^{\mu\nu\lambda\sigma} B^\dagger{}_\nu \partial_\lambda B_\sigma \; \bar{q}\gamma_\mu\gamma^5 q \qquad B^\nu \partial_\mu B^\dagger{}_\nu \; \bar{q}\gamma^\mu q$$

The operators which lead to spin-independent scattering only survive if the vector boson is complex.

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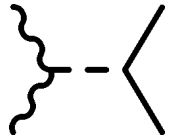
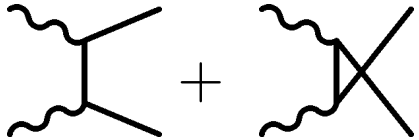
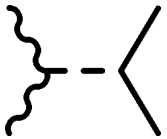
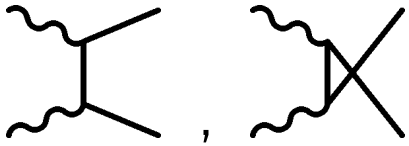
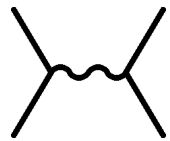
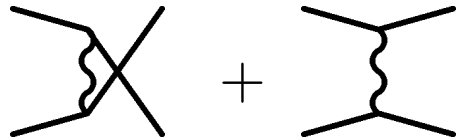
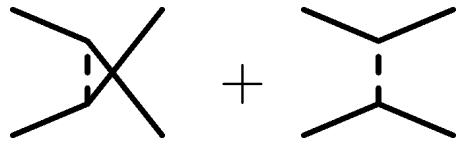
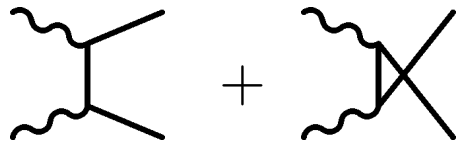
Real Vector Boson

Mediator	Process	Scattering
h		SI
Q		SD (in chiral limit)

Complex Vector Boson

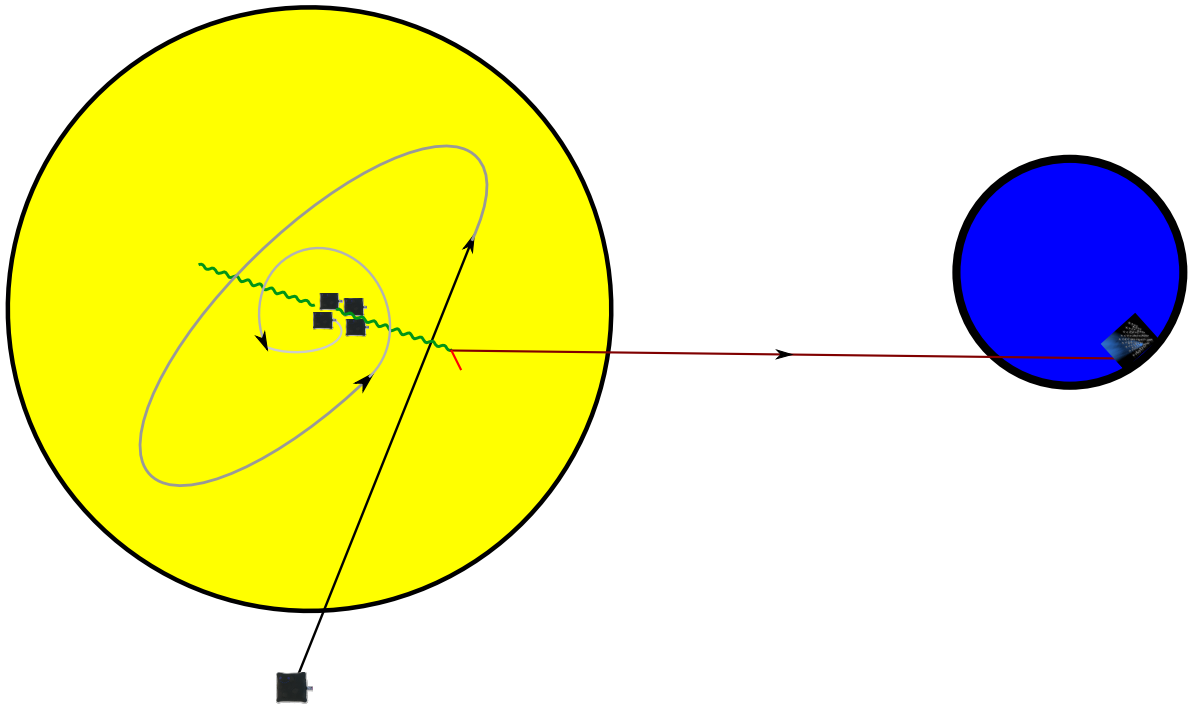
Mediator	Process	Scattering
Z, Z'		SI
h		SI
Q		SI, SD

Models with exclusively spin-dependent couplings

Dark Matter	Mediator	Process	Scattering
Majorana Fermion	Z, Z'		SD
	X		SD (in chiral limit)
	Φ		SD (in chiral limit)
Real Vector	Q		SD (in chiral limit)

IceCube

Spin-dependent dark matter detector



Capture $\rightarrow$ Annihilation $\rightarrow$ Decay $\rightarrow$ Detection

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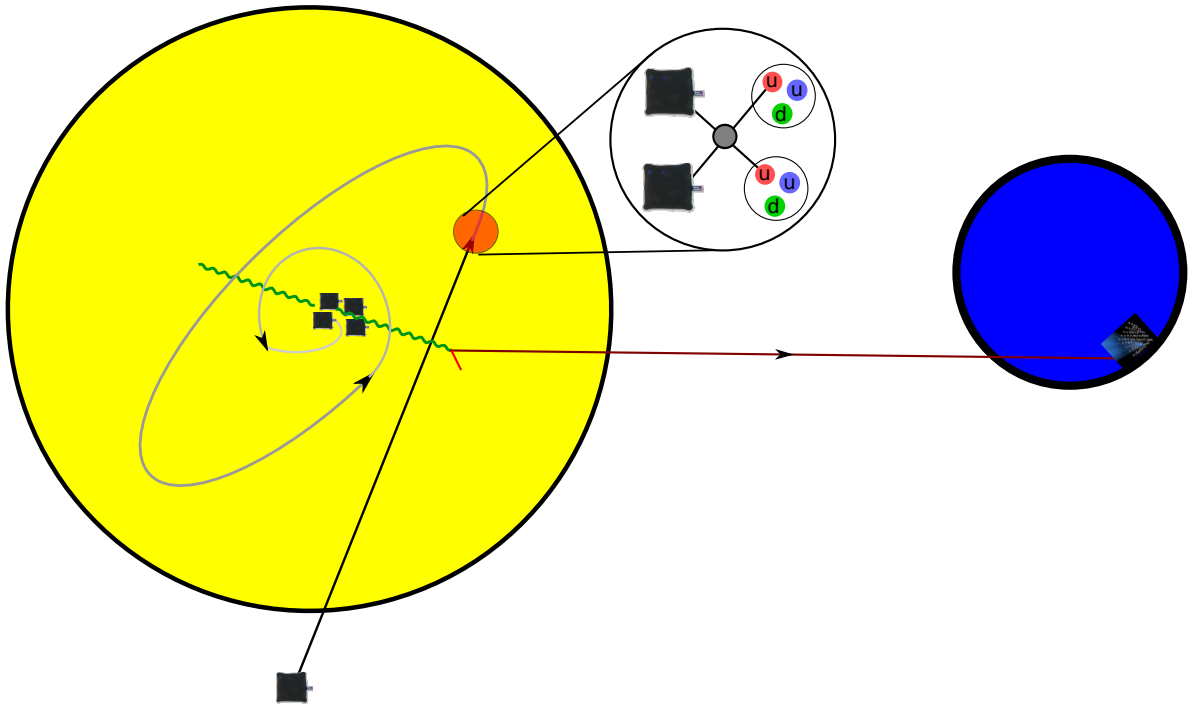

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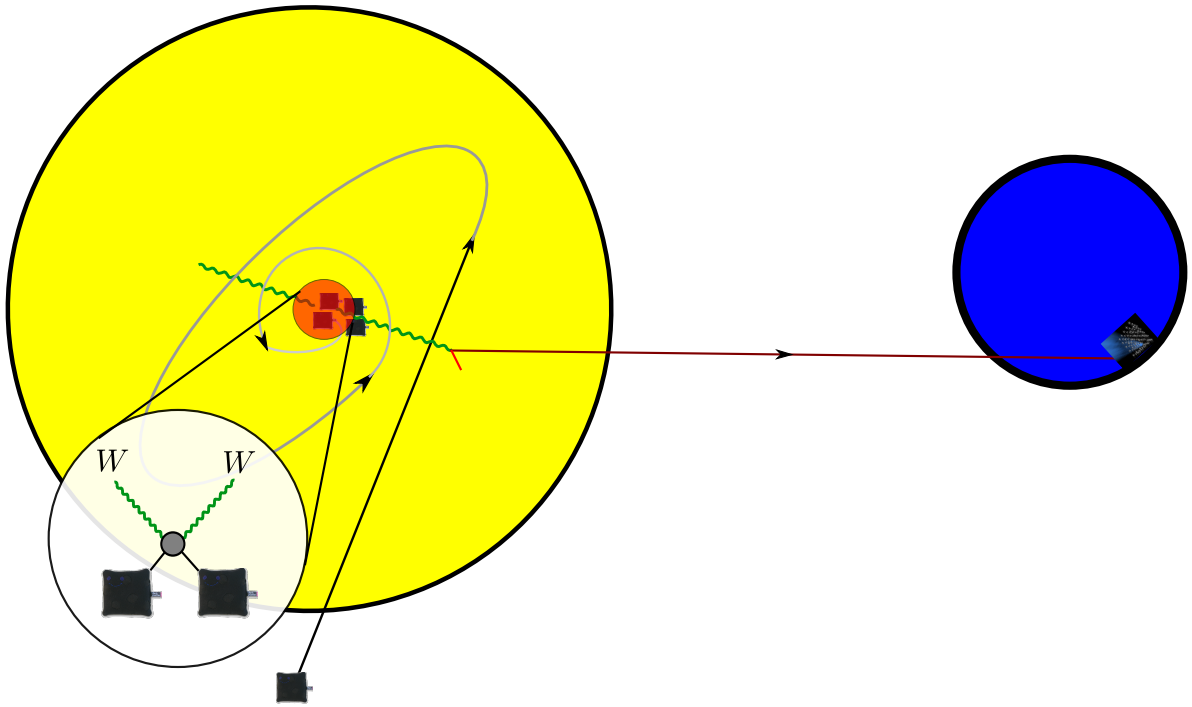

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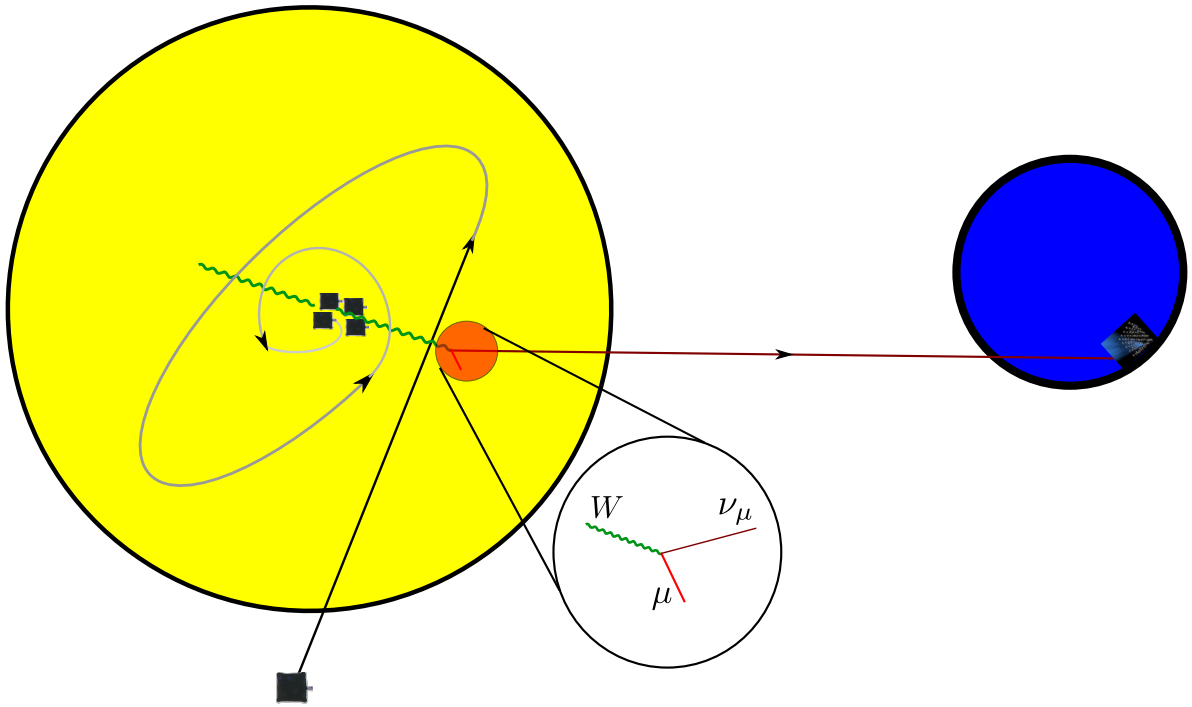

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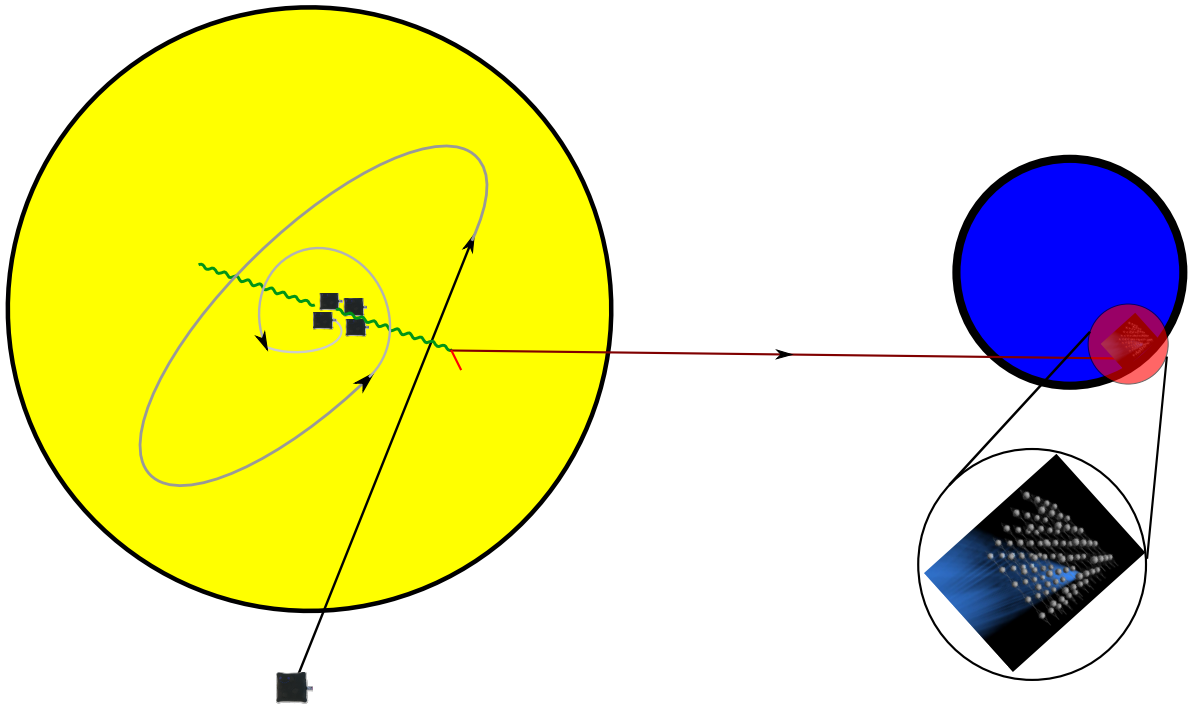

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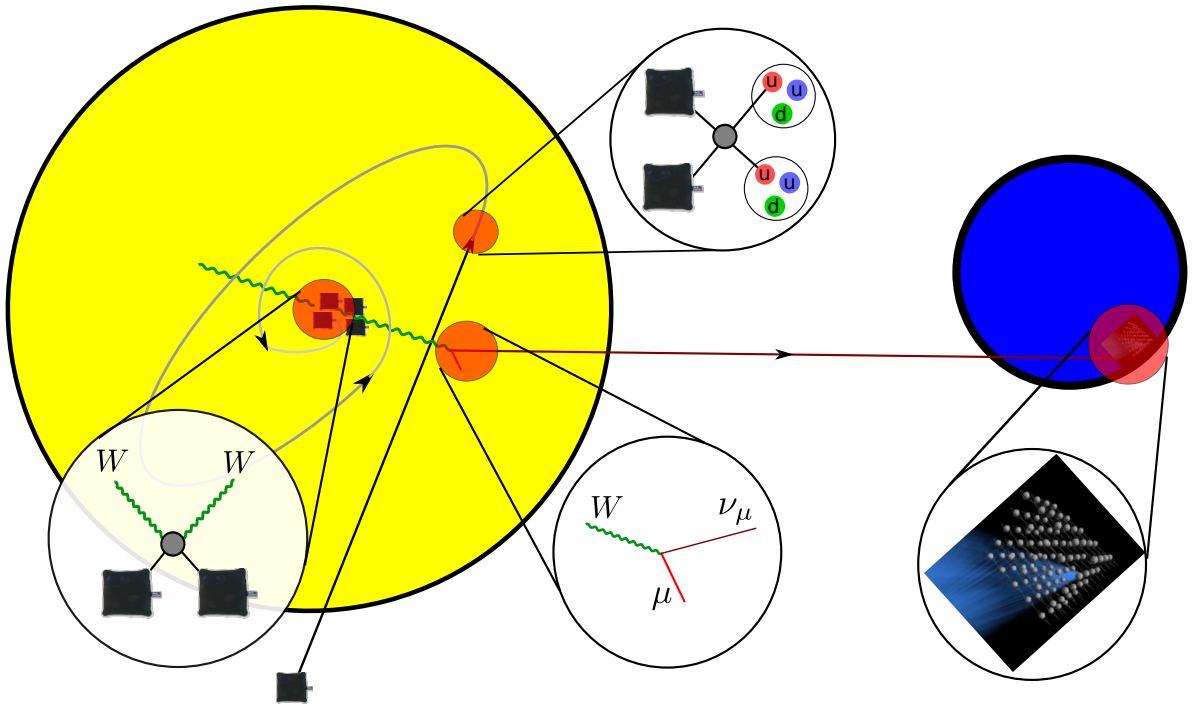
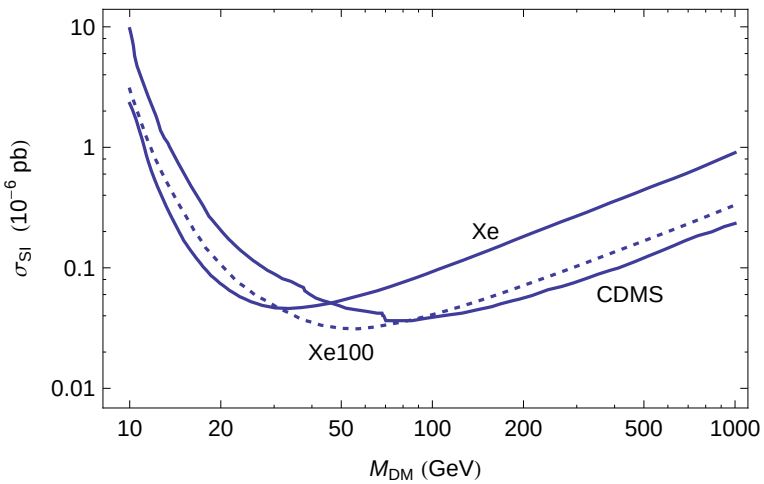


The neutrino signal is bounded by the WIMP-nucleon cross-section.

Direct Detection bounds

The bound on spin-independent interaction is much stronger than the corresponding bound on spin-dependent interaction.



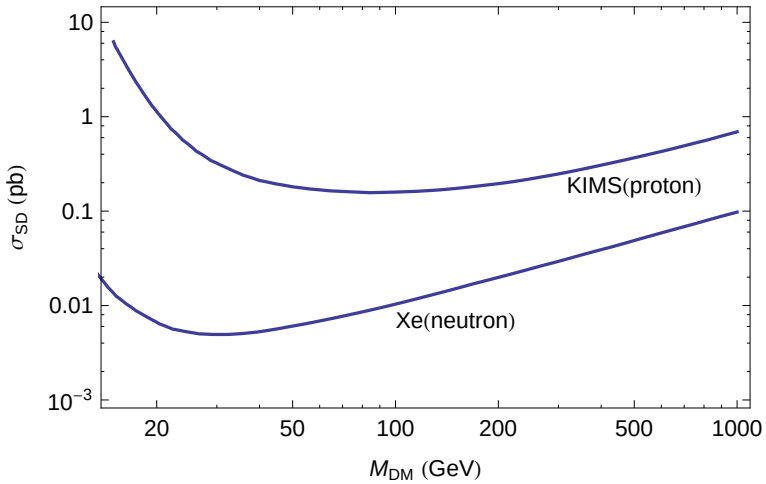


Figure: WIMP-nucleon cross-section bounds

We use the bounds from direct detection to calculate the maximum signal in IceCube.

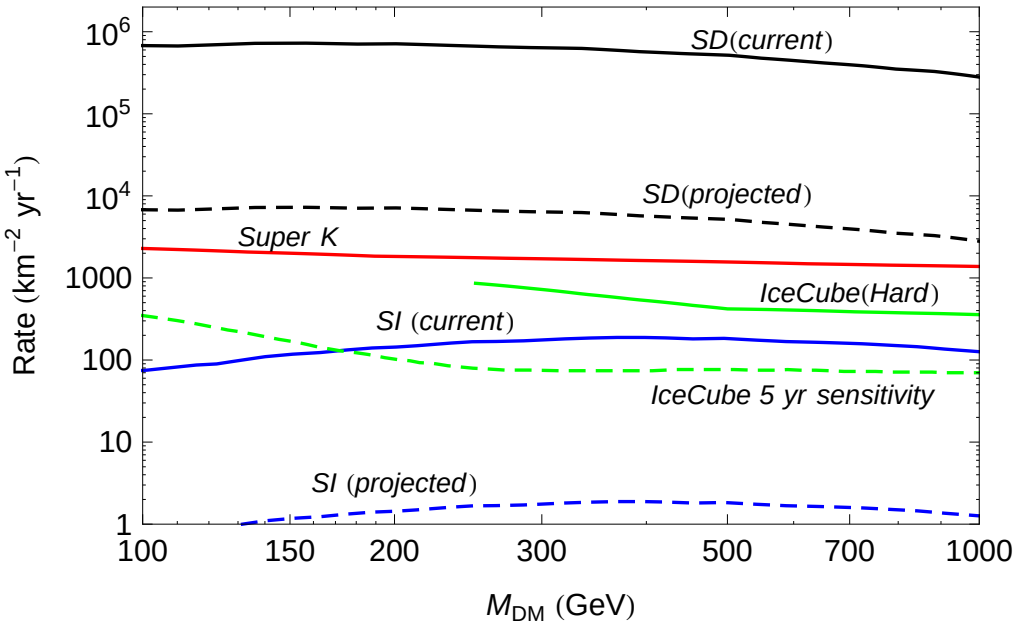


Figure: Rate in IceCube assuming W^+W^- final state

Conclusion

- We highlight a new approach to the question of dark matter. Using a combination of current experiments, we seek to answer basic questions in dark matter physics, without specializing to a specific model.
- As an example, we see that if neutrino telescopes see a signal in the near future, while current direct detection experiments do not, we have shown that the favored scenario is that the dark matter is its own anti-particle.